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Twentieth century trends in tree ring stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) of *Larix sibirica* under dry conditions in the forest steppe in Siberia

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[1] Tree ring width, density, and ratio of stable isotopes ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) in wood and cellulose were determined for larch (*Larix sibirica* Ledeb.) growing under water deficit conditions in the forest steppe zone in central Siberia (54°24′N, 89°57′E) for the period 1850–2005. Dendroclimatic analysis of the chronologies indicated precipitation to be the most important factor determining indicated parameters. Precipitation of June is significantly correlated with tree ring width and maximum density (r = 0.36 and 0.43, $p < 0.05$, respectively). Relations of $\delta^{13}C$ and $\delta^{18}O$ to precipitation are similar, but the most important month is July (r = −0.47, $p < 0.05$ for $\delta^{13}C$; r = −0.29, $p < 0.05$ for $\delta^{18}O$). Further, $\delta^{18}O$ is positively related to the mean temperatures of July (r = 0.30, $p < 0.05$). Carbon and oxygen isotope ratios in wood and cellulose showed strong negative trends for the last 100 years. The reason for this decrease could be the observed shift of the beginning of the vegetation period to earlier dates (up to 1 week) in spring and the increased use of precipitation water stored in the soil from October of the previous year, although other explanations cannot be excluded (in particular the physiological effect of increasing atmospheric CO_2 also responsible for lower $\delta^{13}C$ values). Thus, an earlier start of the vegetation period could lead to tree ring formation during a period with higher water availability, resulting in stronger isotopic fractionation and ^{13}C depletion, also reflected in a higher earlywood to latewood ratio. At the same time, highly ^{18}O depleted water from October precipitation of the previous year is absorbed. The incorporation of this isotopically lighter water during photosynthesis is reflected in the wood and cellulose of tree rings.

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1. Introduction

[2] Boreal forests in Siberia (Russia) provide an ideal possibility to investigate the influence of climate on forest ecosystems due to a wide variety of vegetation and climate conditions over this vast territory. Dendroecological and dendroclimatological approaches are among the most reliable tools to estimate the response of forest vegetation to a changing environment [*Briffa et al.*, 2001; *Wirth et al.*, 2002; *Knorre et al.*, 2006]. So far, dendrochronological studies focused in the north (wet and cold climate) on summer temperature reconstructions [*Vaganov et al.*, 1996; *Naurzbaev et al.*, 2002], and in the south (dry, warm conditions) on reconstructions of lake levels, rainfalls, annual river runoff and fire regime [*Valendik et al.*, 1993; *Andreev et al.*, 1999, 2001; *Magda and Zelenova*, 2002]. In most studies, tree ring width was used as the only dendrochronological parameter, and only few authors included tree ring structure [*Vaganov et al.*, 1999; *Kirdyanov et al.*, 2003; *Silkin and Kirdyanov*, 2003].

[3] The use of stable (C, O, and N) isotopes in ecosystems and climate research studies has become an additional well established tool to reveal plant responses to a changing environment [*Borella et al.*, 1998; *Saurer et al.*, 2004; *Körner et al.*, 2005; *Pelz et al.*, 2005] and to improve our understanding of the climate-plant interaction in the past and present [*McCarroll and Loader*, 2004; *Gagen et al.*, 2007; *Sidorova et al.*, 2008]. It is known that the incorporation of the main elements and the ratio between the light and heavy elements during carbon, oxygen and nitrogen uptake for the biosynthesis of organic matter reflects envi-

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ronmental conditions [*Farquhar et al.*, 1989a, 1989b; *Farquhar and Lloyd*, 1993; *Anderson et al.*, 1998; *Leavitt et al.*, 2001; *Dawson and Siegwolf*, 2007]. Hence, data on the natural abundance of isotopic composition have proven to be very useful for climate reconstructions [*McCarroll and Loader*, 2004; *Welker et al.*, 2005; *Gagen et al.*, 2007]. Most of these studies concentrated on the regions in America [*Leavitt and Long*, 1986; *Barber et al.*, 2004; *Leavitt et al.*, 2008], Africa [*February*, 1999], and Europe [*Gagen et al.*, 2004; *McCarroll and Loader*, 2004], recently also within large networks (ISONET [*Treydte et al.*, 2007]). Only a few studies were carried out in the north and central part of Eurasia [*Arneth et al.*, 2002; *Saurer et al.*, 2002; *Kagawa et al.*, 2003; *Kirdyanov et al.*, 2008; *Sidorova et al.*, 2008]. Such investigations were mainly carried out for the northern part and the permafrost zones where the temperature regime is the main limiting factor of tree ring growth. Besides using stable isotopes from tree rings for temperature reconstruction in these northern areas, an increasing number of studies applied C and O isotopes to reconstruct ambient humidity and moisture conditions from arid zones [*Barbour et al.*, 2002; *Adams and Kolb*, 2004; *Gagen et al.*, 2004], but no studies are available for the dry regions in Siberia.

[4] A diagnostic enhancement in this field is the multiparametric analytical approach where tree ring width, tree ring density and stable isotopes are used in combination [*Gagen et al.*, 2004; *Kirdyanov et al.*, 2008; *Sidorova et al.*, 2008, 2009]. Due to different environmental factors influencing each parameter differently, the extracted climatic information becomes more reliable.

[5] The environmental change over the twentieth century and particularly over recent decades was rapid and severe and apparently leads to a disagreement between temperature and tree growth response [*D'Arrigo et al.*, 2008]. Also a common trend in the carbon isotope ratio of tree rings was found worldwide, which is a continuous decrease of the $\delta^{13}C$ values in wood and cellulose [*Leavitt and Lara*, 1994; *Arneth et al.*, 2002; *Robertson et al.*, 2004]. This decrease can be partially attributed to the increasing ambient CO_2 concentration (c_a) along with a decrease in $\delta^{13}C$ (Suess effect) and can be corrected based on *Francey et al.* [1999]. Yet it is often noted that the $\delta^{13}C$ chronologies maintain the negative trend during recent decades even after the Suess correction [*Gagen et al.*, 2007; *D'Arrigo et al.*, 2008]. This effect could be due to environmental changes, like the physiological effect of CO_2 on the gas exchange of trees [*Gagen et al.*, 2007], improved soil water conditions caused by melting permafrost in the north [*Sidorova et al.*, 2008] or the use of autumn-winter precipitation during the early growth period in the south. Under such conditions (in the south) the stomatal conductance can be high, since the air to leaf vapor pressure difference is rather low resulting in a low leaf water loss. Furthermore the photosynthetic rate is usually moderate under low temperatures (5°–10°C), such that the leaf intercellular CO_2 concentration (c_i) is relatively high leading to a relatively high c_i/c_a ratio resulting in more negative $\delta^{13}C$ values.

[6] Decreasing $\delta^{18}O$ trends over the twentieth century have also been reported [*Saurer et al.*, 2002]. In late fall and early spring, when the temperatures are low, the precipitation water is more depleted in ^{18}O, which is incorporated during photosynthesis. Such cool conditions in fall and spring lead to isotopic depleted assimilates. While in fall these assimilates are stored in the tree tissue and remobilized in spring, the newly produced carbohydrates are depleted as well, which is then reflected in the earlywood of the tree rings. Thus the early wood growing under cool and moist conditions is isotopically more depleted than in summer. Increasing amounts of annual [*Groisman et al.*, 2005] and winter-spring precipitation [*Ye and Ellison*, 2003] over the last century, as reported for northern Eurasia, can therefore result in decreasing $\delta^{18}O$ trends. The isotopic signals therefore partly reflect a direct climatic impact and partly a physiological response to the environmental conditions [*McCarroll and Loader*, 2004]. Regarding tree ring width and density, physiological effects may dominate changes in the tree ring structure [*Briffa et al.*, 1998; *Vaganov et al.*, 1999].

[7] In this paper, we focus on the following questions: (1) How are the climatic variations between the first and second half of the last 150 years reflected in the tree ring parameters (tree ring width, density, carbon and oxygen isotopes ratios) of living larch trees (*Larix sibirica* Ledeb.)? (2) What are the consequences of a change in water availability for the early growth season in the south of Siberia for tree physiology and tree growth? (3) How does the recently accelerated climate change affect the forest steppe in central Siberia?

2. Material and Methods

[8] The study was conducted in the forest steppe zone in the south of central Siberia (Khakasia, 54°24′N, 89°57′E) (Figure 1). The climate is characterized as highly continental (Figure 2). According to the data from the meteorological station Shira (located in 7 km to the north from the study site) the mean annual temperature for the period 1966–2000 is 1.2°C. The mean monthly temperature is −14°C during the winter period (December–February) and +16°C in summer (June–August). The mean annual amount of precipitation for the period 1936–2000 is 300 mm. Most of the precipitation (about 70%) falls during the summer (June–August).

[9] Siberian larch (*Larix sibirica* Ledeb.) is among the main tree species growing in the forest steppe zone in the region. It forms monodominant or mixed stands with pine (*Pinus sylvestris L.*) and birch (*Betula sp.*). Samples for tree ring analysis were collected in open forest larch stand (distance between trees 10–30 m) formed on the sandy-macadam soils. Ground vegetation of the study site is mainly represented by caespitosa-graminoid (*Carex sp.*, *Calamagrostis sp.*).

[10] Wood cores were sampled in autumn 2005 with an increment borer at breast height from 12 dominant larch trees. Tree ring width (TRW), early wood (EWD), late wood (LWD) and maximum latewood density (MXD) were obtained from density profiles of tree rings measured with the use of a densitometer DENDRO-2003 (Walesch Electronics, Switzerland) according to the procedure described by *Schweingruber* [1988]. The individual TRW and MXD series were standardized to remove nonclimatic age trends in the raw data as follows. A cubic smoothing spline with 50% frequency-response cutoff equal to 2/3 series length was fitted to the individual records and residuals calculated in

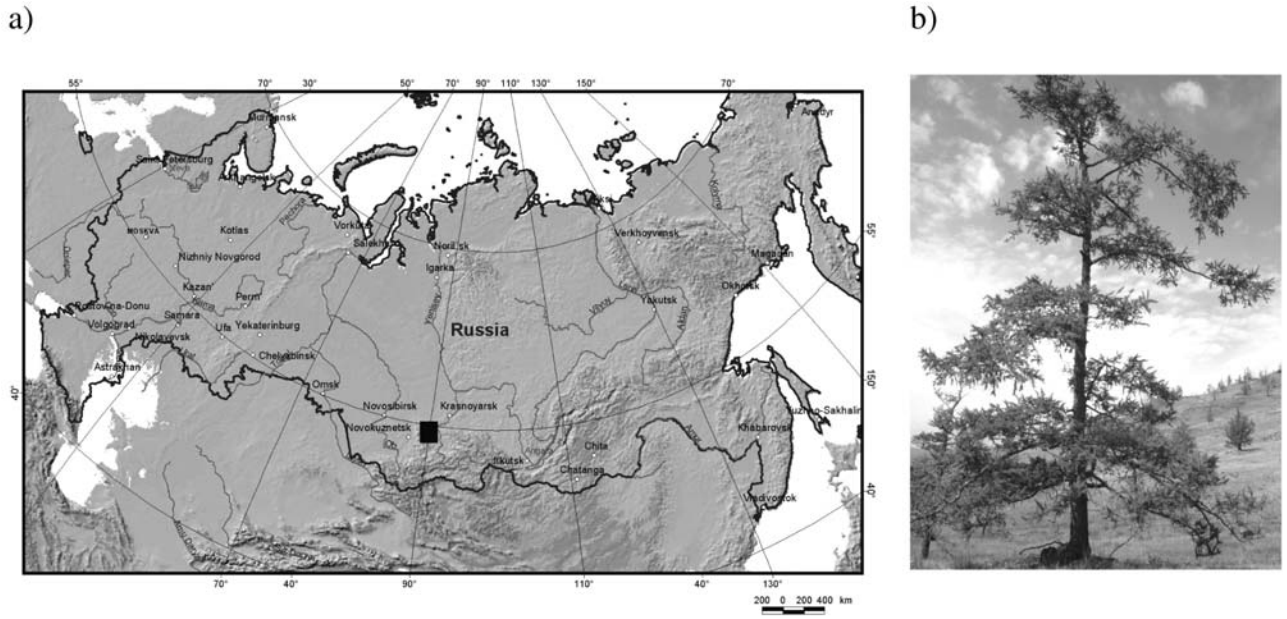

Figure 1. (a) Map with location of study site and (b) photo of *Larix sibirica* Ledeb. from the forest steppe zone of south of central Siberia. Photo courtesy of A. V. Kirdyanov.

ARSTAN. Because of relatively low autocorrelation in tree ring series (first-order autocorrelation was 0.34 and 0.17 for TRW and MXD, respectively) the standard master chronologies were used to preserve long-term changes in tree ring parameters. Signal strength of the chronologies (coherence of year-to-year variations of the tree ring parameters) was estimated by interseries correlation (rbar) and the expressed population signal (EPS) [*Wigley et al.*, 1984]. Theses statistics were calculated as an average of values obtained for a number of 50 year periods lagged by 25 years.

[11] For the isotopic analysis, 5 trees were chosen (2 cores for each tree) from the same sample set. To eliminate the juvenile effect in isotope data, only material from trees older than 200 years at the breast height was measured for the period of 1850–2005. The separate cores were split in a one year resolution. Material for the same year from all the cores was pooled [*Saurer et al.*, 1995; *Borella et al.*, 1998] in accordance with the weight contribution of each sample and milled. Extraction of cellulose was conducted in solutions of 5% NaOH and 7% $NaClO_2$ (sodium chlorite) in accordance to *Loader et al.* [1997]. The isotope analysis for carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) was carried out for whole wood and extracted α cellulose separately. For determination of the C isotope ratio 0.6–0.8 mg were weighted into tin capsules and for the oxygen 1.1–1.3 mg were weighed using silver capsules. The ratios of $^{13}C/^{12}C$ and $^{18}O/^{16}O$ were determined by combustion or thermal pyrolysis, respectively, in an Elemental Analyzer (EA1108, Finnigan, Germany) coupled to a mass spectrometer (Delta S, Finnigan) at the Paul Scherrer Institute (Switzerland). The isotope values are expressed in delta notation relative to the international V-PDB reference for carbon and versus V-SMOW for oxygen. The methods used in this study for isotope analysis are described in detail by *Saurer et al.* [1997]. The obtained carbon isotope data were corrected for the decreasing $\delta^{13}C$ value of the atmospheric CO_2, which is a result of the release of ^{13}C depleted CO_2 originating fossil fuel combustion and biomass burning in the course of land use change. This correction was done relatively to the data interpolated using the high precision records of atmospheric $\delta^{13}C$ obtained from Antarctic ice cores [*Francey et al.*, 1999]. Additionally we used a correction, proposed by *McCarroll et al.* [2009] to take account of possible changes in the response of trees to the increasing availability of CO_2 in the atmosphere. This correction is called as the pin correction or $\delta^{13}C_{pin}$ (the $\delta^{13}C$ values as if they were obtained under preindustrial conditions).

[12] Additionally we measured stable isotope ratios of C and O separately for early and latewood. These measurements were carried out with annual resolution for the

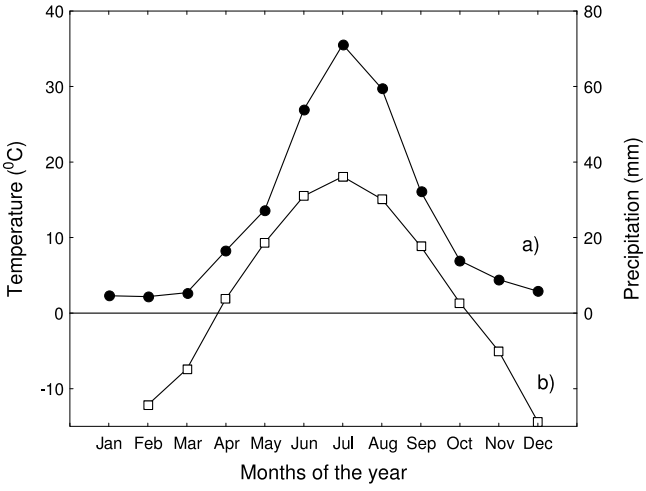

Figure 2. Average values of (a) precipitation (solid dots) and (b) temperature (open squares) of the meteorological station Shira (1966–2000).

Table 1. Time Series Statistics of the Tree Ring Width, Maximum Density Chronologies, and Isotopic Ratios in Wood and Cellulose[a]

Parameters	Period	Number of Trees/Cores	Mean Values	Standard Deviation	Rbar	EPS
TRW (0.01 mm)	1777–2005	12/24	0.78	0.79	0.71	0.95
MXD (g/cm^3)	1777–2005	12/24	0.99	0.16	0.60	0.93
$\delta^{13}C_{wood}$ (‰)	1850–2005	5/10	−22.40	0.71	-	-
$\delta^{13}C_{cell}$ (‰)	1850–2005	5/10	−20.31	0.82	-	-
$\delta^{18}O_{wood}$ (‰)	1850–2005	5/10	23.44	0.84	-	-
$\delta^{18}O_{cell}$ (‰)	1850–2005	5/10	26.64	0.82	-	-

[a]TRW, tree ring width; MXD, maximum density. No Rbar or EPS statistics are presented for isotope series because of pooling.

periods 1849–1853, 1886–1890, 1903–1905, 1948–1955, 1973–1978, 1995–2000 for the same trees that were used for the other isotope analysis, resulting in 29 years for $\delta^{13}C$ and 20 years for $\delta^{18}O$ where we distinguished between earlywood and latewood.

[13] To determine the influence of climate conditions on tree ring growth, correlation analysis between the chronologies and the instrumental records from the nearest meteorological stations (7 km from the site) was carried out. Daily precipitation data were available for the station Shira (54°30′N, 89°56′E) for the period between 1936 and 2000. Daily temperature records cover only the period from 1966 until 2000. Therefore, we used temperature data from the station Minusinsk (53°44′N, 91°49′E) located within 100 km from the study site (1936–2000). Correlation coefficients between monthly temperature data for the two stations are high and range between 0.89 and 0.95 (significant at $p < 0.0001$).

3. Results

3.1. Tree Ring Width, Density, and Stable Isotopes

[14] The length of TRW and MXD chronologies is 229 years while the stable isotope time series are 156 years long (Table 1). Mean tree radial growth and maximum density are 0.78 ± 0.79 mm and 0.99 ± 0.16 g/cm^3, respectively. These tree ring parameters are characterized by high interserial correlations (rbar = 0.60–0.71) and a strong common signal (EPS = 0.93 for 12 trees) and therefore allow the development of population representative site records. Tree ring width and maximum density indices show pronounced decadal-scale variability, but no significant long-term trends during the last 156 years (Figure 3a). However, there are slight negative trends in absolute values of TRW, which can be related to age (tree geometry trend), whereas the measured (uncorrected) values of MXD rise appreciably (not shown). The density was measured separately in earlywood (EWD) and latewood (LWD), where the late wood density increases opposite to the early wood (Figure 4a). These data confirmed that the structure of the tree ring is normal (according to the density data) and was not damaged, e.g., by fungi, etc. The ratio between earlywood width (EWW) and latewood width (LWW) increases slightly during the whole observed period (Figure 4b), and by 13% for the last 100 years.

[15] Mean values of $\delta^{13}C$ are −22.40 ± 0.71‰ for wood material and −20.31 ± 0.82‰ for the extracted cellulose (Table 1 and Figures 3b and 3c). The differences between carbon isotopes ratios in wood and cellulose increase by ca.0.5‰ during the last 156 years (from −1.8‰ for the period 1850–1900 to −2.3‰ for 1950–2000). The average values of the $\delta^{18}O$ in the tree rings are 23.44 ± 0.84‰ in wood and 26.64 ± 0.82‰ in cellulose. The difference in $\delta^{18}O$ values between wood and cellulose also have the tendency to increase in time (from 2.9‰ for the period 1850–1900 to 3.7‰ for 1950–2000).

[16] The comparative analysis of all chronologies showed that there is a strong correlation between the time series during the whole study period (Table 2). There are strong positive relationships between TRW and MXD, and for the isotope series between $\delta^{13}C$ and $\delta^{18}O$. In contrast, TRW and MXD chronologies are negatively related with $\delta^{13}C$ and did not reveal any relationship with $\delta^{18}O$. Moreover, the negative correlation of TRW and MXD with $d^{13}C$ is higher in cellulose, than in wood, while the positive correlation between $\delta^{13}C$ and $\delta^{18}O$ is higher in wood.

[17] Correlation coefficients between TRW and $\delta^{13}C$ chronologies differ between the three consecutive 50 year periods. For the first two periods (1850–1900 and 1900–1950) the relationships between TRW and $\delta^{13}C$ are significantly negative (r = −0.32 − −0.63, $p < 0.05$) both for the wood and cellulose. For the last five decades (1950–2000) the negative correlation for these chronologies becomes insignificant. TRW and $\delta^{18}O$ (in the wood and cellulose) chronologies did not show any significant relations.

[18] The isotope ratio chronologies show negative trends for the last century (Figures 3b and 3c), for both the carbon and oxygen compositions in wood and cellulose. Regarding carbon, it should be kept in mind that these data have already been corrected for the decline of $\delta^{13}C$ in atmospheric CO_2, but still show a decrease. A quantification of these trends shows that the rate of changes in $\delta^{13}C$ and $\delta^{18}O$ as determined from linear regressions are 0.73‰ (for δ^{13}Ccell), 1.26‰ (for δ^{13}Cwood), 1.68‰ (for δ^{18}Owood) and 0.58‰ (for $\delta^{18}O$ cellulose) per 100 years. Decreasing $\delta^{13}C$ and $\delta^{18}O$ values in time could be attributed to increasing earlywood/latewood width ratio, assuming that different ratios of stable isotopes are observed in different parts of the tree ring [*Li et al.*, 2005]. To check this hypothesis we measured stable isotope ratios of C and O separately for the earlywood and latewood (Figures 5a and 5b). Average values of $\delta^{13}C$ in earlywood are −21.93‰ ± 0.89 and −22.01‰ ± 0.87 in latewood and are not statistically different. For $\delta^{18}O$, these values are also very similar, 22.60 ± 1.14 and 22.71‰ ± 1.22, respectively. All the obtained isotope data have a declining tendency during the last 100 years. Despite the fact that the width and density of the early and latewood are different, the ratio of heavy to light isotopes in these structures is about the same.

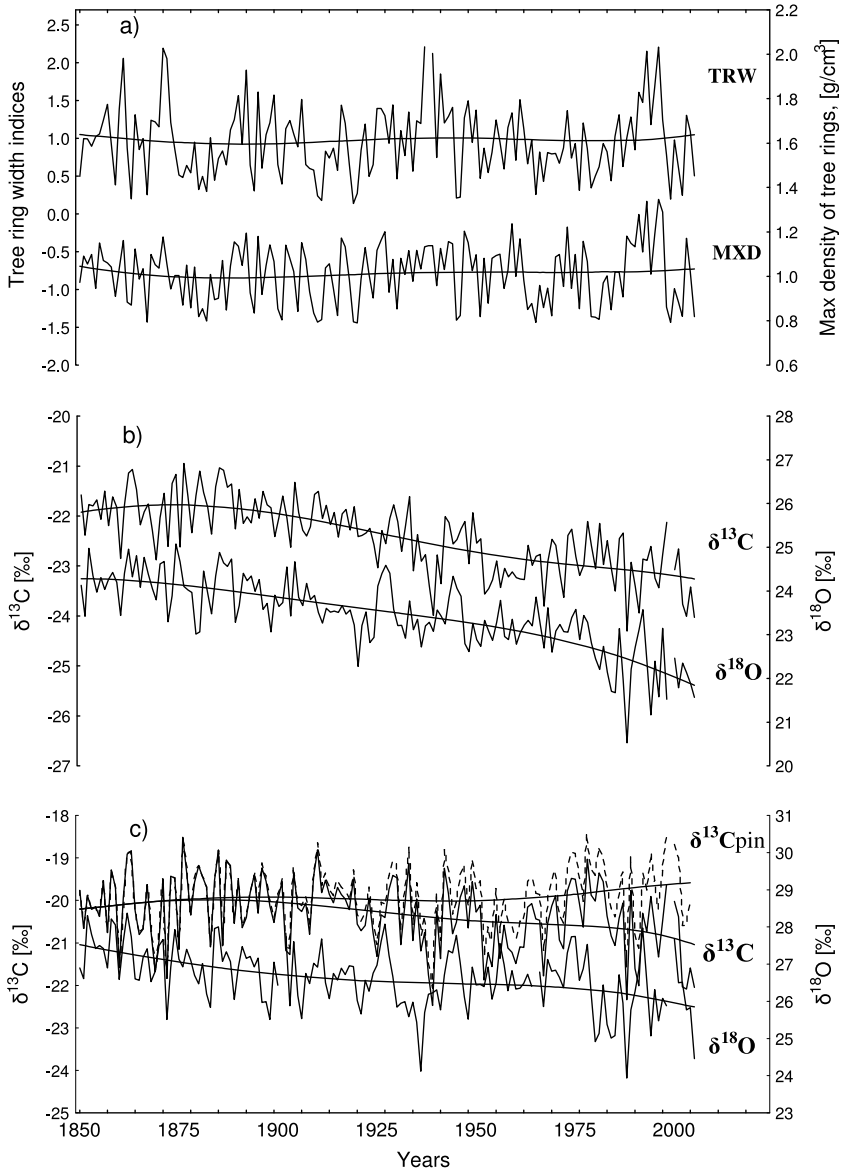

Figure 3. (a) The chronology of tree ring width (TRW) and maximum density (MXD), and the ratio of stable isotopes of carbon and oxygen (b) in wood and (c) in cellulose. Negative exponentially weighted smoothing procedure (Negative Exponential Weighted LS option in STAISTICA 6.0) was applied to smooth the lines.

3.2. Relation Between TRW, MXD, Isotopic Ratio, and Climate Data

[19] To determine differences of the climatic impact in different time periods we have considered the influence of climatic factors on tree ring parameters (Figure 6) for all the available meteorological data (1936–2000) for two equal periods (1936–1968 and 1968–2000) (Table 3).

[20] The main climate factors that influences tree ring width are the amount of June precipitation ($r = 0.43$, $p < 0.05$) and the mean temperature of September of the previous year ($r = -0.47$, $p < 0.05$) (Figure 6a). Climatic response of tree ring growth varied in time. Thus, for period 1936–1968 temperatures of September were negatively correlated and precipitations of May and June are positively correlated with TRW, but for the period after 1968 it turned into a positive relationship with September precipitation of the previous year.

[21] During all investigated periods, the results of the maximum tree ring density are similar to those of ring width (Figure 6b), i.e., high positive correlation coefficients with precipitation of June ($r = 0.36$, $p < 0.05$) and September of the previous year ($r = 0.38$, $p < 0.05$). Moreover there is a negative relationships with the temperature for the same months ($r = -0.28$, $p < 0.05$ for June and $r = -0.43$, $p < 0.05$ for September of previous year). Intercorrelation between climate data of these months is insignificant. The negative impact of previous year autumn temperature is significant for the period 1936–1968 only; the relationship with summer precipitation however is stable during all the considered periods. After 1968 the amount of September precipitation of the previous year becomes more relevant for maximum

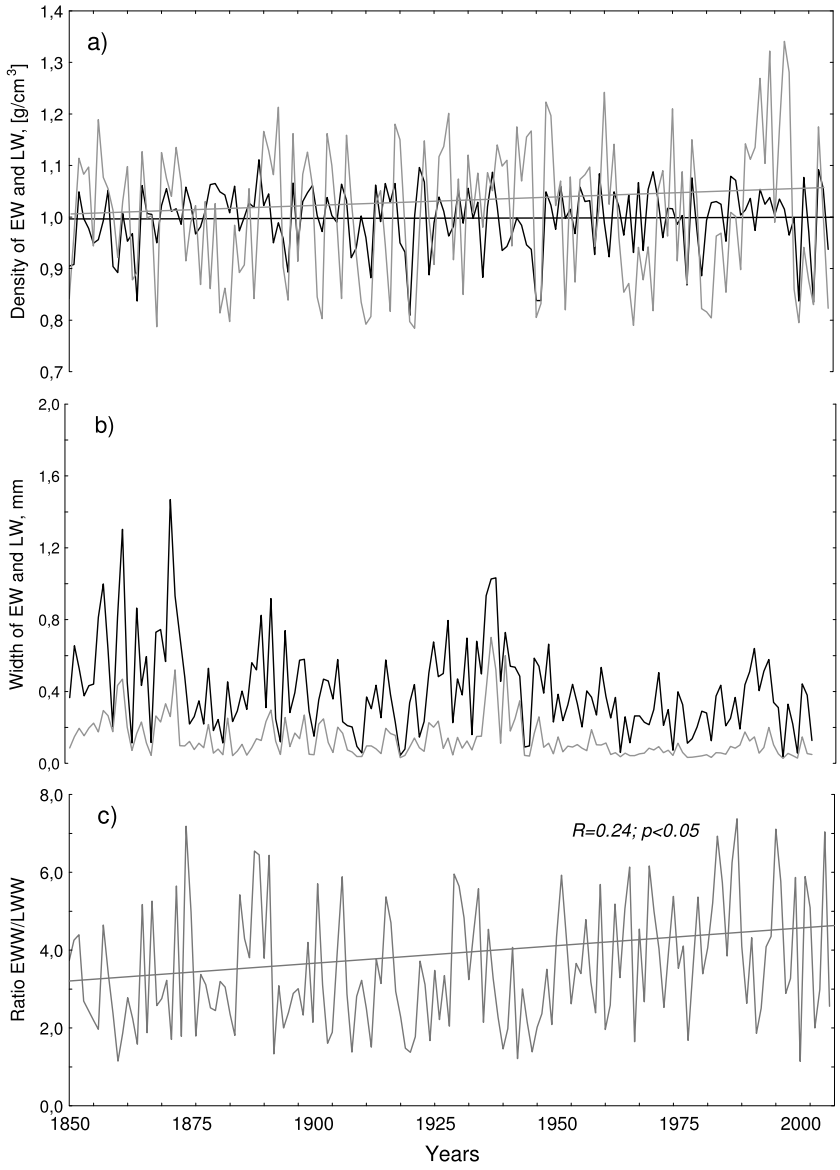

Figure 4. Index values of earlywood density (EWD, black line) and latewood density (LWD, gray line). (a) Straight lines illustrate nonsignificant trends ($p > 0.05$), (b) raw chronologies of earlywood width (EWW, black line) and latewood width (LWW, gray line), and (c) the ratio between earlywood width and latewood width (EWW/LWW).

density. Earlywood and latewood density shows similar with MXD reaction to weather condition of September of previous year and July of this year (Figures 6c and 6d). But the response of EWD and LWD to weather during the vegetation period is differing. The amount of spring precipitation is more important at the time when earlywood is forming (r = 0.36, $p < 0.05$ for April and r = 0.28, $p < 0.05$ for May). Latewood density depends on the amount of June precipitation (r = 0.36, $p < 0.05$). Moreover, the relation of these parameters is not stable in time (Table 3).

[22] The main factor that influences the carbon isotope variation is the amount of precipitation (Figures 6e and 6f). In wood the $\delta^{13}C$ is negatively and significantly related to precipitation of July (r = −0.47, $p < 0.05$), in cellulose it correlates with precipitation of June and July (r = −0.34, $p < 0.05$; r = −0.47, $p < 0.05$, respectively). These relationships

Table 2. The Correlation Coefficients Between the Observed Chronologies of Tree Ring Width, Maximum Density, and Ratio of the Stable C and O Isotopes in Wood and Cellulose[a]

	TRW	MXD	$^{13}C_{wood}$	$^{13}C_{cell}$	$^{18}O_{wood}$	$^{18}O_{cell}$
TRW	1.00					
MXD	0.80	1.00				
$^{13}C_{wood}$	−0.20	−0.22	1.00			
$^{13}C_{cell}$	−0.31	−0.32	0.81	1.00		
$^{18}O_{wood}$	-	-	0.63	0.35	1.00	
$^{18}O_{cell}$	-	-	0.47	0.39	0.74	1.00

[a]TRW, tree ring width; MXD, maximum density; $p < 0.005$.

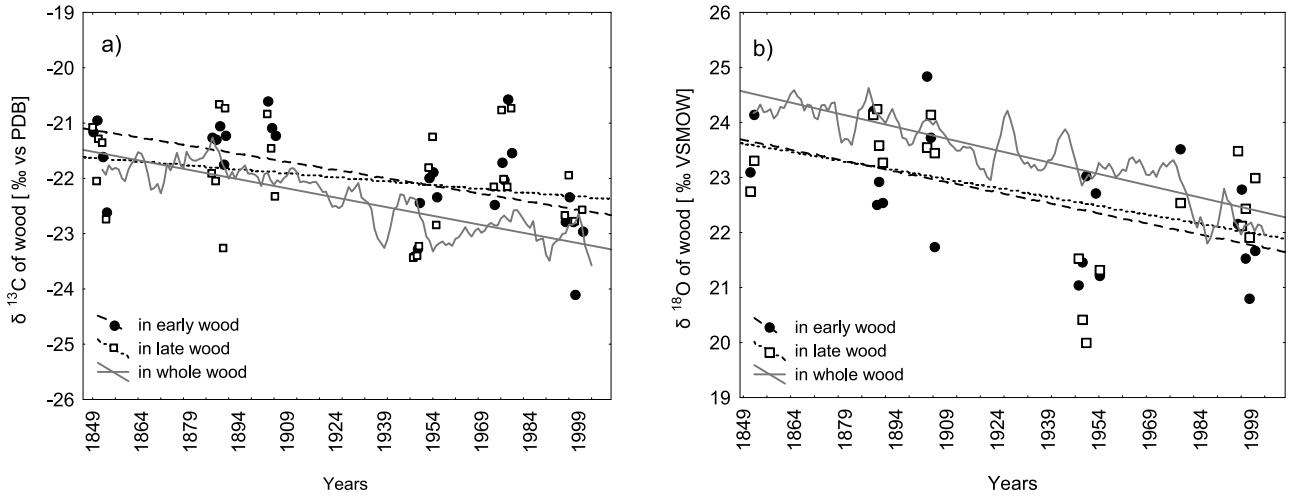

Figure 5. Values of (a) δ^{13}C and (b) δ^{18}O in the earlywood (solid circles) and latewood (open squares) obtained for the individual years and smoothed by 5 years for whole wood. The regression lines (not significant at $p < 0.05$) are also shown.

are stable over time for wood. For cellulose the precipitation of June is more important after 1968, in comparison the period 1936–1968 when we found the significant correlation of δ^{13}C with July precipitation. No significant correlation between δ^{13}C and monthly temperatures was found.

[23] The δ^{18}O in wood does not reveal any close relationship to the climate (Figures 6g and 6h), but for δ^{18}O in cellulose there is a negative correlation with July precipitations ($r = -0.29$, $p < 0.05$) and positive correlation with July temperature ($r = 0.30$, $p < 0.05$). For the 1936–1968 period the autumn precipitation was not significantly related to δ^{18}O values, but there was a close relationship to the temperatures of May for wood and cellulose and June for cellulose only. After 1968 the determining factors were reversed: high temperatures of May and high amounts of precipitation of July were negatively related to stable oxygen ratios.

[24] Well-defined long-term trends in the curves of δ^{13} C and δ^{18}O might be the reason for some relations between the chronologies themselves, and between the chronologies and climate. Therefore, we carried out the procedure of removing trends with 2/3 series long spline [*Cook and Krusic*, 2005] and checked all the relationships again. Most significant changes in correlations after the standardization procedure were noted for relations between δ^{13}C and δ^{18}O in the wood where correlation coefficients reduced from 0.63 to 0.22. Smaller differences were noted for relations between $\delta^{13}C_{wood}$ and $\delta^{18}O_{cell}$ (reduced from 0.47 to 0.31) and $\delta^{18}O_{wood}$ and $\delta^{13}C_{cell}$ (reduced from 0.35 to 0.18). Such differences are closely related with the removal of the long-term trends in wood for both isotopes. Relationships between standardized isotope curves for cellulose do not change much. No correlation coefficients between isotope and climate data changed significantly after removing trends.

[25] To investigate the seasonal course of climate, we calculated mean pentad temperatures (averaged for consecutive 5 days) from daily data of the meteorological station in Minusinsk (Figure 7a) for the same two periods as used above (1936–1967 and 1968–2000). Averaged temperature data for consecutive days show that in the last 4 decades the vegetation period starts approximately 5 days earlier. Monthly temperatures of May according to both the Minusinsk and Shira weather stations are increased by 2°C in the last 40 years (Figure 7b). We calculated the temporal trends of monthly precipitation from 1936 to 2000 with linear regression (Figure 7c). There is a decrease in summer precipitation apparent ($p < 0.05$ for July), while winter precipitation, in particular in October, increased.

4. Discussion

[26] A new set of tree ring data, including ring width, density, C and O isotope composition was obtained in tree rings from a region with extreme climatic conditions in the forest steppe in Siberia (dry and warm in summer, long, cold winter). As a major result we found that precipitation is the main climatic factor, which controls tree ring growth of larch in this region. Further, the chronologies established by the different parameters of tree rings in the arid region of central Siberia showed significant long-term trends during the last 156 years.

[27] The correlation analysis between TRW, MXD and climate indicated a changing impact of climatic factors during the period of observation. Before the 1970s, precipitation in spring and early summer had the strongest impact on tree ring parameters, but for the last decades the amount of precipitation in September and particularly October of the previous year has become increasingly important. At the same time negative correlations with temperatures of September of the previous year were observed for TRW and MXD chronologies for the whole period of instrumental meteorological data (1936–2000). Analyses of climate data show an increase of the average monthly temperatures year around, except for June, July, August, and September. The most significant increase in temperature is observed for May (3°C, significant at $p < 0.002$). The amount of precipitation in these months slightly decreases after 1960s. According to phenological data by *Butorina* [1979] the threshold temperature for the beginning

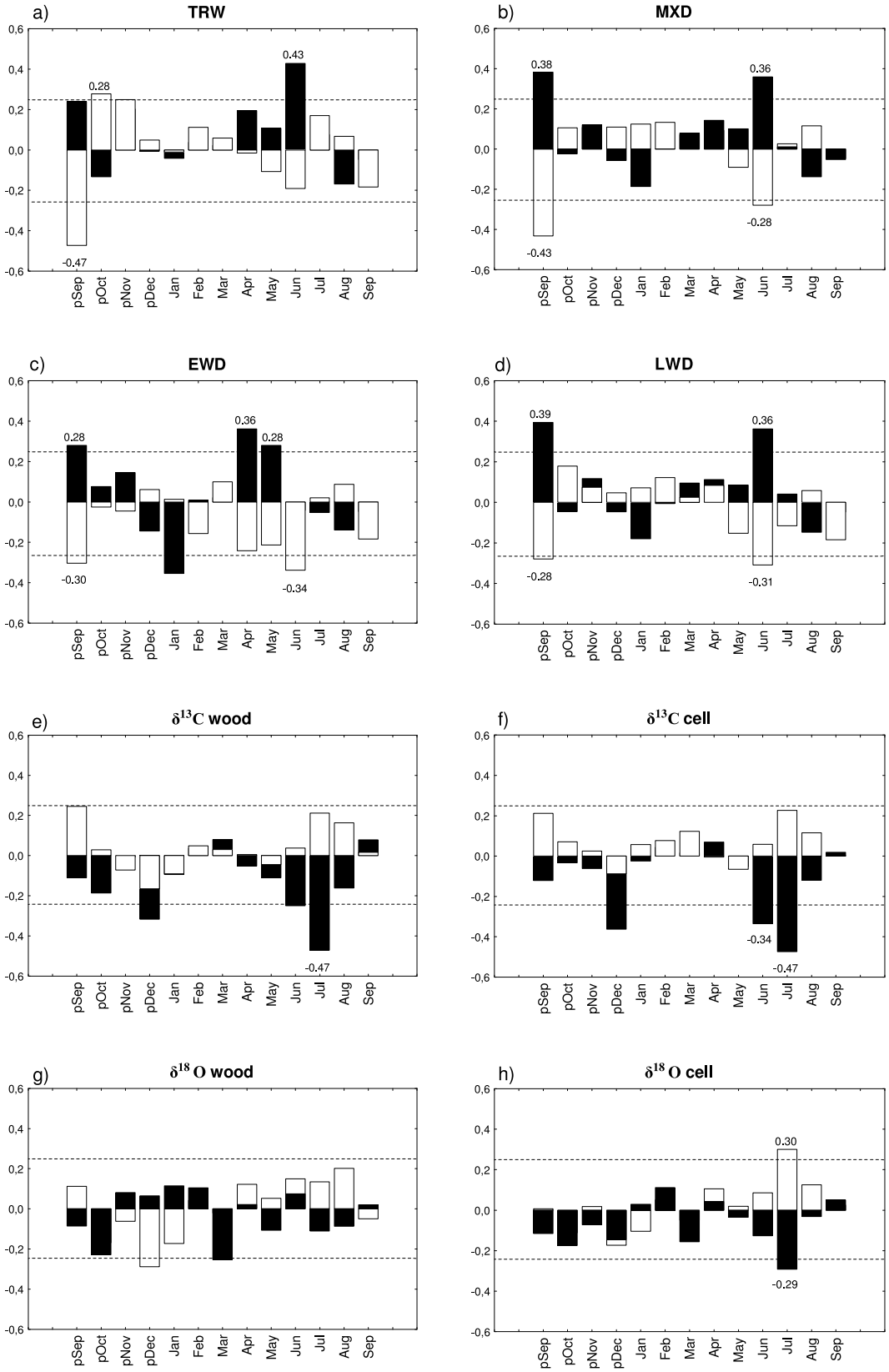

Figure 6. Correlation coefficients of all obtained chronologies with mean temperature values (white bar) and mean amount of precipitation (black bar) for the period 1936–2000.

Table 3. Significant Correlations Between Tree Ring Parameters TRW, MXD, $\delta^{13}C$, and $\delta^{18}O$ and Climatic Data, $\frac{T}{P}$, for Two Equal Periods[a]

	1936–1968				1968–2000			
	Sep_{pr}[b]	May	Jun	Jul	Sep_{pr}[b]	May	Jun	Jul
TRW	**−0.50**	−0.34	−0.25	−0.19	−0.18	0.06	−0.31	0.26
	0.12	**0.39**	**0.48**	0.17	**0.57**	−0.14	0.16	−0.11
EWD	−0.34	−0.26	**−0.35**	−0.11	−0.27	−0.11	−0.34	0.18
	0.41	0.13	0.01	−0.14	0.20	**0.41**	−0.10	0.11
LWD	**−0.37**	**−0.40**	−0.26	−0.34	−0.13	0.12	−0.31	−0.02
	0.27	0.34	0.34	0.20	**0.50**	−0.12	**0.42**	−0.09
MXD	**−0.40**	**−0.37**	−0.26	−0.32	−0.10	0.12	−0.33	−0.01
	0.27	0.34	0.34	0.15	**0.49**	−0.09	**0.41**	−0.09
$\delta^{13}C_{wood}$	0.04	0.03	−0.04	0.05	−0.07	−0.08	0.13	0.32
	−0.03	−0.16	−0.16	**−0.44**	−0.25	−0.10	−0.34	**−0.46**
$\delta^{13}C_{cell}$	−0.01	0.10	0.00	0.17	0.14	−0.20	0.21	0.18
	0.03	−0.16	−0.17	**−0.50**	−0.30	−0.06	**−0.47**	0.34
$\delta^{18}O_{wood}$	−0.01	**0.40**	0.28	0.11	−0.14	−0.31	0.08	0.07
	−0.14	−0.16	−0.02	−0.12	−0.22	0.02	−0.01	−0.25
$\delta^{18}O_{cell}$	−0.03	**0.49**	**0.35**	0.28	−0.20	**−0.38**	−0.02	0.30
	−0.14	−0.19	−0.29	−0.23	−0.19	0.07	−0.11	−0.34

[a]At statistical threshold equal to 0.35. Bold indicates significant correlation coefficients (at $p < 0.05$); all other values are not significant.
[b]Sep_{pr}, September of previous year.

of the vegetation period in the region is approximately 3°C with the sum of positive daily temperatures being 17°–20°C. Averaged data of temperatures for 5 consecutive days show that during the last four decades the start of the vegetation period shifted to 5 days earlier (Figure 7a). *Smith et al.* [2004] indicated that the onset dates of thawing in spring and freezing in autumn advanced 5–7 days in Eurasia over the period 1988–2002, leading to an earlier start of the growing season but no change in its length. Monthly temperature of May both in the Minusinsk and Shira stations increased by 2–3°C accordingly in the last 40 years. These facts together with the remote sensing [*Delbart et al.*, 2008] and climate simulation data [*Schwartz et al.*, 2006] indicate a shift of the beginning of the vegetation period toward earlier dates in this region. Higher temperatures in the beginning of the growing season and the earlier start of the vegetation period can lead to an increase of the earlywood width as its formation starts earlier in vegetation period (Figure 4c). These changes in seasonality also have an impact on the isotope signatures.

[28] While the precipitation for October doubled after 1968 (Figure 7b), the mean air temperatures falls below 0°C during this time of the year, so that most of the precipitation infiltrated into the soil freezes or/and remains as snow cover. As the October precipitation amounts to about 50% of the sum of the winter precipitation (November–March), this water is of particular importance for tree growth, as it is then available for trees in the early growing season of the following year. An increased soil water supply from the previous year during the initial part of the tree ring's growing period and wood structure formation at temperatures that are favorable for growth will lead to higher stomatal conductance, increased discrimination against ^{13}C isotopes, and thus lower (more negative) $\delta^{13}C$ values [*Farquhar et al.*, 1989a, 1989b].

[29] *Li et al.* [2005] showed for Chinese pine trees that the main reason for a negative trend in $\delta^{13}C$ could be an increase of the EW/LW ratio over time, in combination with distinctively more ^{13}C depleted earlywood (which is usually more enriched in ^{13}C than latewood; see *Helle and Schleser* [2004] or *Jaggi et al.* [2002, 2003] for *Picea abies* in Switzerland). However, in our study we did not find a significant isotope difference between EW and LW, therefore the long-term trend in 13C cannot only be explained by the observed increase in EW/LW ratio according to *Li et al.* [2005]. Nevertheless, our hypothesis of an important physiological effect of the favorable growth conditions during the early part of the growing season is supported by the increase of the EW/LW ratio. Further, a prolonged and moderate photosynthetic activity (as temperatures are still low) in the first period of the earlywood formation with a preferred assimilation of ^{12}C due to more favorable conditions (enough water and temperatures in a range for a moderate photosynthetic activity) may be reflected in both EW and LW isotope ratio, and therefore partly explain the observed gradual decrease in $\delta^{13}C$ during the last decades.

[30] With regard to the oxygen isotopes, the higher proportion of winter precipitation, which is strongly ^{18}O depleted ("light") compared to summer precipitation amount, could be important. This effect is enhanced by the parallel reduction in summer precipitation. Accordingly, the ratio of winter to summer precipitation available for the trees has increased over the recent decades. This infiltrated water from winter, stored in a frozen form or as snow, is incorporated by the trees as soon as it is melted and available at the beginning of the growing season (the most active part of tree ring formation [see *Vaganov and Shashkin*, 2000; *Vaganov et al.*, 2006]). This could explain in part the decreasing trend in $\delta^{18}O$ in tree rings. An additional amplification of this effect is caused by an accelerated soil thawing by 20 April, and a warming of the soil up to 10°C at a soil depth of 30 cm by 20 May [*Butorina*, 1979]. Thus the earlier vegetation period along with soil warming (before the

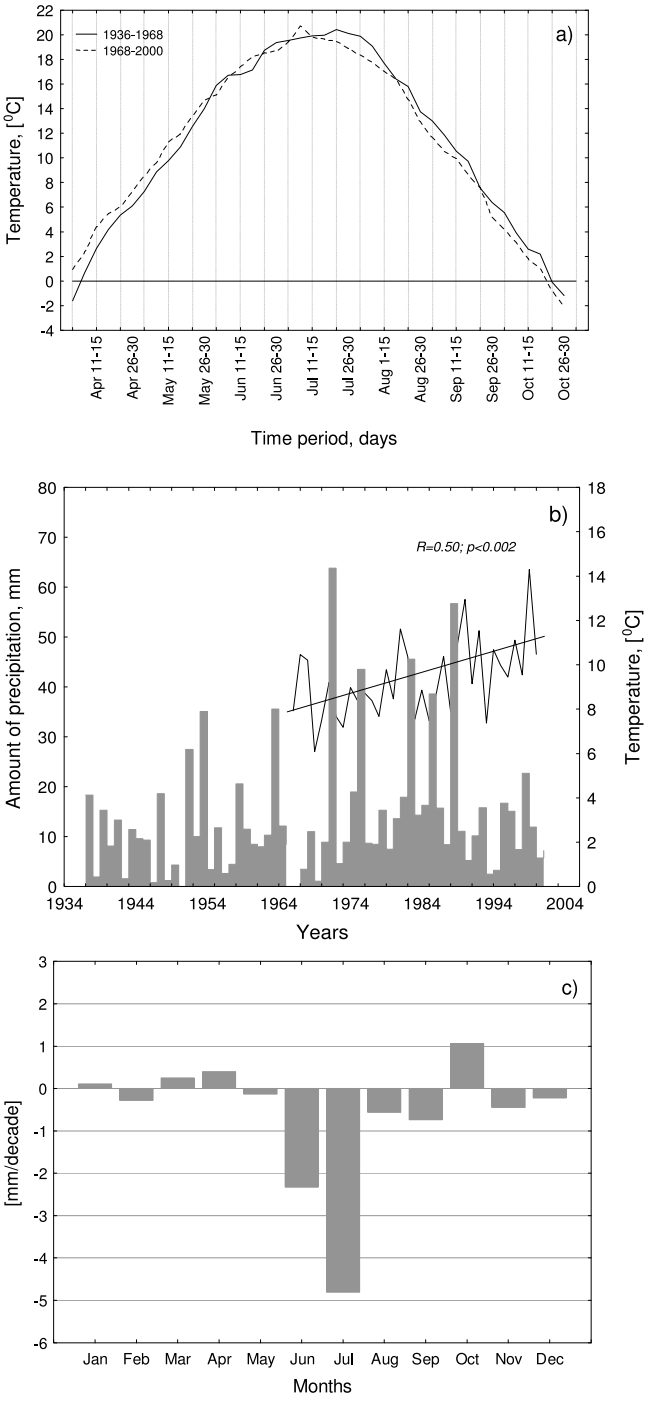

Figure 7. (a) Temperature regime of the studied region calculated by mean values of 5 days for the period from April to October (average for the two time intervals 1936–1968 and 1968–2000) according to data of meteostation Minusinsk; (b) raw data of May temperature (line) and October precipitation (bars) according to data of meteostation Shira; (c) temporal trends of monthly precipitation (mm/decade) (linear trend from 1936 to 2000).

soil water is enriched by evaporation from the topsoil) might enhance this phenomenon.

[31] Decreasing total amount of precipitation (by 49 mm) and increasing mean temperatures (by 0.3°C) of the vegetation period (April–September) during the last few decades can possibly lead to an increase of drought stress for plants. A reduced water supply results in a reduction of the stomatal conductance and reduced biomass production. An increase in temperature besides a diminished precipitation will increase VPD (Vapor Pressure Deficit) and thus intensify the drought situation, with an enhanced effect on the physiology of the trees (enhanced stomatal closure and reduced photosynthetic C assimilation and more positive $\delta^{13}C$ values in the latewood). This should be reflected in a long-term increase of the C- and O isotope ratio, as the stomata close. A decrease in tree ring width would be a clear indication for reduction in biomass production as a result of a reduced photosynthetic capacity. Conclusively we would expect a decrease in the tree ring width and an increase in the $\delta^{13}C$ and $\delta^{18}O$ values in the tree rings (as a symptom of drought stress), whereas we found the opposite trend for both isotope values and a constant tree ring width and density over the last 150 years but even more so in the last 60 years. The declining trend in $\delta^{13}C$ is therefore most likely not related to increasing drought stress. The negative trend in $\delta^{13}C$ also cannot be explained with the declining $\delta^{13}C$ of the atmosphere [*Leavitt and Lara*, 1994; *Robertson et al.*, 2004] as we have corrected our data accordingly [*Francey et al.*, 1999].

[32] To evaluate if this might be a CO_2 fertilization effect we applied the $\delta^{13}C$-pin ("preindustrial") correction according to the model by *McCarroll et al.* [2009]. In this model, trees may respond in an active or passive way to increasing atmospheric CO_2. As the amount of CO_2 in the air (ca) increases, trees may respond by increasing their water use efficiency so that the ratio of internal (ci) to ambient CO_2 remains constant ("active response"). Accordingly, also $\delta^{13}C$ values remain stable. In recent decades, however, many trees seem to have reached the limits of this active response and they are no longer able to maintain a constant ci/ca ratio, so that the internal concentration of CO_2 has increased ("passive response"), leading to a decline in $\delta^{13}C$. The correction is a constrained nonlinear detrending of the $\delta^{13}C$ series after AD 1850 and the constraints are based on the likely physiological response of trees to increased CO_2. Indeed the $\delta^{13}C$ values of our data set slightly increased or stayed unchanged after the pin correction (see Figure 3c), indicating that the observed declining tree ring ^{13}C trend in our study could be a direct response to the increasing CO_2. Some other evidence is, however, not consistent with this hypothesis. First, it cannot explain why the presented TRW data did not respond to an increasing atmospheric CO_2. Further, in general we can state that an increase in $\delta^{13}C$ is the result of an increase in net photosynthesis at a given (±constant) stomatal conductance or vice versa a decrease in stomatal conductance at a given (±constant) net photosynthesis. If in this case the stomata were closing as a response to an increasing CO_2, it would also have to be reflected in an increasing $\delta^{18}O$ curve [see *Farquhar and Lloyd*, 1993], while tree ring width stays constant or slightly increases if the photosynthetic rate increases as well. But the decreasing $\delta^{18}O$ data of this study suggests more likely and increased availability of ^{18}O

depleted water from the previous fall and winter precipitation along with an increase in the stomatal conductance, and a moderate photosynthetic rate.

5. Conclusion

[33] The significant climatic changes (shift of the beginning of the vegetation period, a decrease of the precipitation in summer and an increase in September/October and an increased water availability in spring) were not as well reflected in the tree ring parameters as normally found for temperate regions. However, these climatic changes could not yet be translated into tree physiological signals reflecting changes in temperature, water availability and precipitation because the major changes affect the seasons when the physiological processes are strongly diminished and no (winter) or little growth (September/October) occurs.

[34] Nevertheless our data reveal a climatic change, namely a shift of the vegetation period by 5–7 days to an earlier date in the course of the last century. The trees are still strongly climate controlled, which is well reflected in the isotopic and tree growth response patterns. Although the summer precipitation was reduced with an increasing mean temperature during the growing season for the region of Khakasia, the doubled amount of precipitation in October compensated the changes in the summer months. This resulted in declining trends for the C and O isotope chronology at a constant tree ring width in particular for the last 60 years. The relatively high abundance of water early in the vegetation period seems to change the earlywood/latewood ratio, while the earlywood is formed from mostly ^{18}O depleted water under highly ^{13}C discriminating conditions (high water supply and moderate temperatures with moderate photosynthetic rates), whereas the increased drought during the summer months masks the lower $\delta^{13}C$ values of the late wood.

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